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Spectroradiometer Characterization for Colorimetry of LEDs

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ABSTRACT

The uncertainties in color measurements of LEDs by spectroradiometers can be much larger than those for traditional broadband sources due to the quasi-monochromatic nature of LED spectra. In this paper, the uncertainties in chromaticity of LEDs due to bandpass, scanning intervals, and wavelength errors, are analyzed by simulation. Based on the analysis, a spectroradiometer for colorimetry of LEDs has been designed and built at NIST and characterized for uncertainties in measured chromaticity coordinates and other color quantities.

Key words: chromaticity coordinate, colorimetry, LED, spectroradiometry, spectroradiometer

1. INTRODUCTION

The use of Light Emitting Diodes (LEDs) is now expanding in many applications such as for traffic lights, roadway barricade lights, automotive lights, marine and airport signaling, and color displays. Accurate measurements of colors of LEDs with appropriate uncertainty statements are essential in applications where colors are specified by international standards and federal regulations.

Colors (chromaticity coordinates and dominant wavelength) of LEDs are commonly measured with spectroradiometers. Because of the quasi-monochromatic nature of LED spectra, however, the uncertainties of spectroradiometric measurements of LEDs are typically much larger than those of traditional broadband light sources (incandescent lamps and discharge lamps). Uncertainty values of commercial spectroradiometers are often shown, in their catalogs, for measurement of CIE Illuminant A, which is the source typically used for calibration of spectroradiometers. Such uncertainty values are almost useless for the measurement of LEDs as well as for displays.

While general information is available on characterization and calibration of spectroradiometers [1], the effects of various characteristics of spectroradiometers on LED color measurements have not been well studied. To clarify the uncertainties in measured chromaticity of LEDs, the effects of bandpass, scanning interval, and wavelength errors have been analyzed by simulation. Based on the analysis, a spectroradiometer for colorimetry of LEDs has been designed and built at NIST and characterized for the slit function, bandpass, wavelength errors, stray light, and noise. From these analyses, the uncertainties in measured LED chromaticity coordinates x, y and u', v' are discussed.

2. ANALYSIS ON BANDPASS AND SCANNING INTERVAL

The bandpass of a spectroradiometer has an important effect on the accuracy of measured color quantities of light sources. CIE 15.2 [2] recommends a data interval of 5 nm or less, but does not mention bandwidth. CIE 127 [3] recommends wavelength resolution (interpreted as bandwidth and scanning interval) of 1 nm or less for spectroradiometric measurement of LEDs. However, no commercial diode-array (or CCD-array) type spectroradiometers, in the authors knowledge, employs 1 nm bandwidth. Bandwidths of 5 nm to 10 nm are typically used, in spite of much smaller scanning intervals. Thus, the uncertainties of measurements of LEDs using various bandwidths, in relation with the scanning intervals, need to be clarified.

A simulation has been made on a spectroradiometer having various bandwidths, measuring an LED of varied peak wavelength and varied spectral width. Some aspects of this analysis were previously reported [4]. The spectroradiometer simulation calculated convolutions of the source spectra and the slit function. The slit function is set to be a symmetrical triangular function of varied bandwidth. The LED spectrum was modeled using a Gaussian function [4].

Figure 1 shows the results - the errors in chromaticity x (upper figure) and y (middle figure) and dominant wavelength (bottom figure) for the spectroradiometer bandwidth of 10 nm FWHM (full width half maximum) with scanning intervals of 10 nm (matched to the bandwidth), for the LED spectrum with its peak wavelength varied from 400 nm to 700 nm at 2.5 nm intervals (horizontal axis). The three curves show the results for the LED spectral width of 40 nm, 20 nm (typical of actual LEDs), and 1 nm (simulating line emission). The curve for 1 nm oscillates because the error varies depending on where the line emission falls between wavelength scanning points. The maximum error of 0.007 in y is observed for the 20 nm LED model. For comparison, the error for the spectrum of CIE Illuminant A for the same 10 nm bandwidth is calculated to be less than 0.00007 in x, y. The error for LEDs can be 100 times larger.

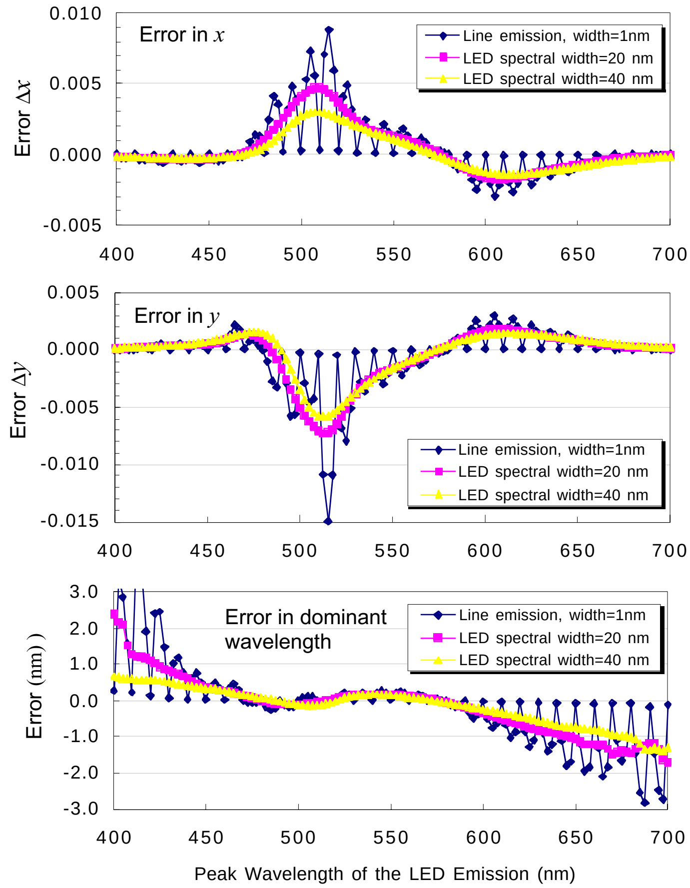

Figure 1. Errors in chromaticity x, y and dominant wavelength with a spectroradiometer of a 10 nm bandwidth and 10 nm scanning interval, for the LED model spectrum peaking at 400 nm to 700 nm, with a spectral width of 40 nm, 20 nm, and 1 nm.

The results indicate that the errors in x, y are most critical for blue-green LEDs peaking around the 500 nm to 520 nm region where the spectrum locus on the CIE x, y chromaticity diagram has the largest curvature. The error in dominant wavelength, however, is not significant in the middle of the visible region. It is interesting to note that the errors cross zero at around 580 nm where the nonlinearity in the chromaticity diagram reverses [4]. Reducing the scanning interval to 5 nm or to 1 nm, keeping the same bandwidth, gave almost the same results and does not reduce the errors. Plots of the same results in u', v' show maximum errors of ~0.004 in the blue and red regions. From these results, it can be said that 10 nm bandwidth is not acceptable for practical measurement of LEDs. Another simulation for a 5 nm bandwidth with a 5 nm interval of a spectroradiometer showed maximum errors of 0.0018 in x, y and 0.0008 in u', v', which are about 1/4 of the errors for a 10 nm bandwidth and considered acceptable for most practical measurements. The use of 2.5 nm bandwidth or smaller would assure this type of error to be within 0.001 in x, y or u', v' for the most critical applications. However, reducing the bandwidth leads to reduced signal levels, which can cause another source of error. It would also be possible to apply corrections for the bandpass-associated errors using the results as presented here. Further simulations also showed that the shape of the slit function (trapezoidal) and the match to the scanning interval are not as critical as the bandwidth itself. These results should be verified by analyzing real LED spectra, some of which have a sharper peak than the Gaussian function.

3. ANALYSIS ON WAVELENGTH ERRORS

The wavelength error of a spectroradiometer is another significant source of error in spectroradiometry of LEDs. A calculation was made using the LED model of a 20 nm spectral width with varied peak wavelength. Figure 2 shows the error in chromaticity (x, y) and (u , v) of the LED model at a varied peak wavelength for the case when the wavelength scale of the spectroradiometer is simply shifted by 1 nm throughout the spectral region. The results show that the error can be as much as 0.025 in y (at ~500 nm) for a 1 nm shift of wavelength. For comparison, the same calculation for CIE Illuminant A shows an error of only 0.0006 in y. This is a simple calculation assuming a 100 % correlation of wavelength errors to show how important an accurate wavelength calibration is for a spectroradiometer to measure LEDs.

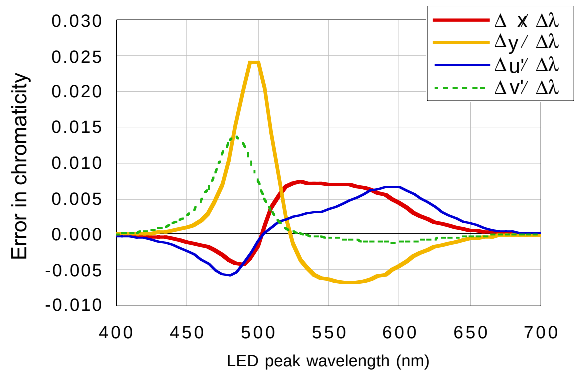

Figure 2. Errors in chromaticity (x, y) and (u ,v) of the LED model (20 nm spectral width) at a varied peak wavelength, for a 1 nm shift in the wavelength scale of the spectroradiometer.

4. CHARACTERIZATION OF THE NIST SPECTRORADIOMETER FOR LEDS

A reference spectroradiometer has been developed for calibration of LEDs at NIST. The spectroradiometer, as shown in Fig. 3, employs a double-grating, scanning monochromator (concave grating, 1200 lines/mm, F4.2, subtractive mode) covering a spectral range from 360 nm to 830 nm. The input optics are designed for irradiance geometry with a 7.5 cm integrating sphere having a 15 mm circular entrance aperture and a 5 mm x 20 mm rectangular output opening, the image of which is focused onto the entrance slit of the monochromator, overfilling the slit. The spectroradiometer is calibrated against an integrating sphere source (15 cm, 2856 K), which is periodically calibrated against the NIST spectral irradiance scale.

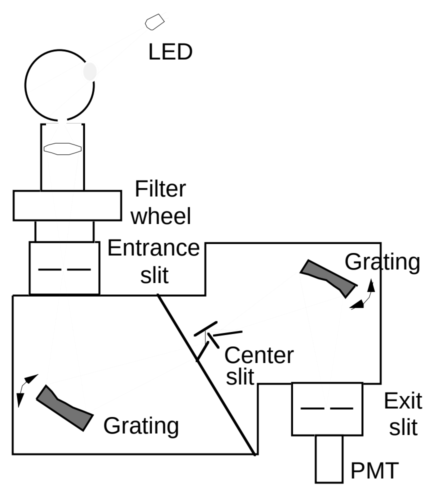

Figure 3. Arrangement of the NIST reference spectroradiometer for LED color measurement.

The spectroradiometer was calibrated and characterized for the 5 nm and 1 nm bandwidth (FWHM). The widths of the entrance/exit slits and the center slit of the monochromator were adjusted, by iterative operation, to obtain the best triangular shape of the slit function with its bandwidth as constant as possible throughout the visible region for each bandpass condition, as shown in Fig.4.

The wavelength scale has been calibrated in the range from 404.7 nm to 763.5 nm using 13 emission

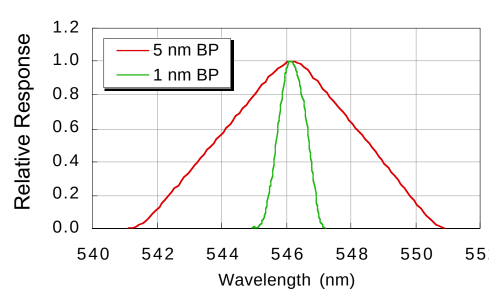

Figure 4. Slit function of the NIST spectroradiometer at 546.07 nm.

lines (9 for 5 nm bandwidth) of lasers and discharge lamps. The results were fitted to a second order polynomial function for each as shown in Fig. 5. These points in the figure were obtained as the centroid wavelength of the measured slit function for each emission line. After the correction using the polynomials, the wavelength errors are within 0.11 nm, and the standard uncertainty is calculated to be 0.63 nm. The expanded uncertainty in chromaticity x, y depends on the color of test LED, and was calculated to be 0.0011 in x, y (k=2) at its maximum (~500 nm), using the numerical method [5] assuming no correlation between values.

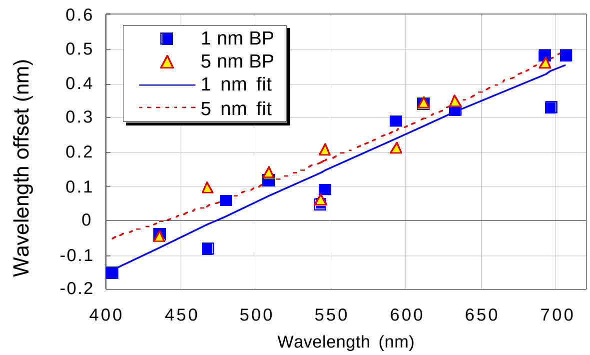

Figure 5. Results of the wavelength scale calibration of the spectroradiometer.

The sources of uncertainty in spectroradiometric color measurement of a light source include the bandwidth, scanning interval, wavelength error, stray light of monochromator, detector linearity, polarization, and random noise of the signal, as well as the uncertainty in the reference standard for spectral irradiance. In addition, the characteristics of LEDs including stability, repeatability, and temperature-dependence of color also affect the measurement result.

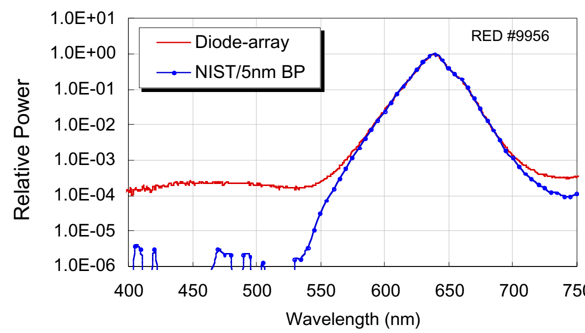

Figure 6. Spectral power distribution of a red LED in log scale, measured with a commercial diode-array spectroradiometer and the NIST spectroradiometer.

The effect of the monochromator bandpass was analyzed as described in Section 2. No correction is applied to the 1 nm bandpass data, but corrections are applied to the data with 5 nm bandpass based on the results shown in Fig. 1. The residual expanded uncertainty after the correction is estimated to be within 0.0005 (k=2) in x, y at the most sensitive wavelength region. For verification, several LEDs (peak wavelengths: 478 nm, 534 nm, 591 nm, and 628 nm) were measured with the calibrated NIST spectroradiometer using both 5 nm and 1 nm bandwidths. After the bandwidth correction for the 5 nm bandpass data, the results in x, y agreed to within 0.0010. This small discrepancy is speculated to be contributions from other uncertainty components, particularly the wavelength uncertainty.

The stray light of the monochromator is more critical for LEDs than for broadband sources. The stray light in the NIST spectroradiometer has been measured to be less than 10^{-6} for typical LED measurements and proved to be negligible. However, stray light in a single grating monochromator can be serious for LEDs. Figure 6 shows an example of the comparison of measurement of a red LED with a commercial diode-array spectrometer and the NIST spectroradiometer, shown on a log scale. In this case the difference in (x, y) was (0.002, 0.0005). This level of stray light would have negligible effect on the measurement of broadband white-light sources, but not for LEDs. The uncertainty in random noise has also been analyzed using the numerical method [5], and proved to be not significant.

5. CONCLUSIONS

The effects of bandpass, scanning intervals, and wavelength errors of a spectroradiometer on color measurement of LEDs have been studied, and a spectroradiometer for colorimetry of LEDs has been developed at NIST. The spectroradiometer has been characterized, and important uncertainty components analyzed. The final uncertainty budget for the NIST spectroradiometer is in progress to establish calibration services on color quantities of LEDs. This work was conducted when Kr nicz stayed at NIST under the U.S.- Hungarian agreement on scientific cooperation.

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